STRATEGY RESEARCH PROJECT

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BATTLEFIELD ROBOTS FOR ARMY XXI

BY

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ABSTRACT

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TITLE: Battlefield Robots for Army XXI

FORMAT: Strategy Research Project

DATE: June 1997 PAGES: 56 CLASSIFICATION: Unclassified

Robotics may well represent the greatest unfulfilled technological promise of the late twentieth century[i], and perhaps nowhere is this more true than in the area of *military robotics*. Closer examination of this issue suggests a compelling question. Is this failure due to technological immaturity or simply our collective inability (or unwillingness) to exploit technologic opportunity? For this paper to be meaningful, I believe it is necessary to retain the distinction between descriptive analysis and prescriptive advice. As such, the paper begins with an historical perspective, followed by an analysis of the technologies relevant to military robotics. That done, we move on to look at some representative unmanned systems, followed by a projection beyond the Army XXI period of interest into the more distant future.

The paper then shifts its attention to developing a coherent set of recommendations regarding the appropriate initiatives in battlefield robots for the Army of the years 2000-2010, often termed "Army XXI." The principal focus will be in the area of unmanned vehicles, as it is here that military robots seem to exhibit their most distinct identity. Such a paper is extremely topical given the ongoing discussions at the highest levels of the Army regarding the allocation of scarce modernization resources, both for Army XXI and the Army after 2010 (the so-called "Army After Next"). I believe it is imperative that we carefully and objectively evaluate the current status of this potentially revolutionary technology and make some informed, deliberate choices based on that information. General Dennis Reimer, the Army Chief of Staff, has stated that we must find new ways of doing business that are both more efficient and effective. Robotics has long been touted as just such a technology, especially by industry and the research community. However, as we all know, actual successes to date have been much less impressive, making this kind of reassessment overdue.

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HISTORICAL PERSPECTIVE

WHAT ONE MAN CAN IMAGINE, ANOTHER MAN CAN DO.

Jules Verne

Automata (from the Greek *automatos*, "acting of itself") have generally fascinated people since ancient times. In the second century B.C., Hero of Alexander is purported to have constructed *automata* that were animated by water, air, and steam pressure. The eighteenth century saw the creation of very intricate, animated dolls which were undoubtedly the by-product of the miniaturization of clock-making technology.[ii]

In 1921, the Czech playwright, Karel Capek, captured the world's imagination with his play *Rossum's Universal Robots* (R.U.R.). Indeed, it was from this work that Capek is credited with coining the word "robot" which derives from the Czech *robata*, meaning "forced labor or serfdom."[iii] (In the play, these anthropomorphic robots rebel and eliminate humanity). R.U.R. raised the specter of a potential threat which certainly has not been realized, but one which recent films, such as *The Terminator*, suggest may yet remain for some still distant, future time.

The dawn of the real world of battlefield robotic systems, however, had already occurred. Though never employed in combat, "E.E. Wilchersham, an engineer with the Caterpillar Tractor Company, designed and developed a remotely controlled demolitions carrier... called the Land Torpedo."[iv] This circa 1918 unmanned ground vehicle (UGV) was battery powered and operated under remote control via cable. World War II saw the actual introduction of such systems to the battlefield, notably the German UGV called the Goliath. Over 7000 of these systems were produced. Being about five feet long and two feet wide, these small tracked vehicles could carry up to two hundred pounds of explosive at a top speed

of about five miles per hour.[v] While used primarily against pill boxes and to clear minefields, they were also lethal against battle tanks. In June, 1942, the German 300th Panzer Regiment (a unit equipped entirely by Goliath-type, remote-controlled tanks carrying high explosives) besieged the Russians at Sebastopol. While generally ineffective, probably due to being used in small numbers and being relatively easily stopped by bad terrain and small arms fire, they did demonstrate that they "could knock out a fully-secured tank in the open at a radius of as much as 50 yards."[vi]

World War I also saw the beginnings of the use of military unmanned aerial vehicles (UAVs). Using a gyro-stabilization unit developed for aircraft in 1915, the U.S. Navy initiated a flying bomb program called the Curtis flying bomb. Based on a Curtis airframe, this device was not radio controlled, but rather flew a prescribed course. Once over the intended target, the engine would stop and the wings dropped off, thus causing the explosive-packed fuselage to dive on its intended target.[vii] Not to be outdone, the Army initiated a UAV program under Charles Kettering of Dayton, Ohio. The final design, widely termed the "Kettering Bug," was also essentially a conventional biplane which carried "a 180-pound bomb a distance of 40 miles at 55 mph."[viii] It was successfully flown on October 22, 1918, only a month before the war ended. World War II saw even greater efforts in this area. Remote-controlled, bomb-laden airplanes saw service both in the Pacific as well as the European theaters. In fact, it was a bomb-laden, remote controlled B-24 in which Joseph Kennedy was killed when it exploded before he could execute his preplanned bailout. Perhaps no World War II UAV is better known than the forerunner to the modern cruise missile, namely the German V-1 Buzz Bomb.[ix]

Unmanned vehicles proved themselves decisively during the 1973 Arab-Israeli War. Having suffered staggering losses of manned aircraft while trying to overcome Egyptian air

defenses, the Israelis decided to employ the Teledyne Ryan AQM-91 and Northrop Chukar remotely piloted vehicles (RPVs) to draw Egyptian fire. Manned Israeli bombers then attacked those defenses while they were reloading with devastating results. Later in 1982 the Israelis used the Scout and Mastiff UAVs (essentially remote-controlled model airplanes with TV cameras) to spoof Syrian air defenses. Manned Israeli aircraft then knocked them out with anti-radiation missiles. The Israelis also performed aerial reconnaissance during those UAV missions.

Two UAVs that came and went during the 1980s were the Lockheed-developed Aquila and the Developmental Sciences-produced Skyeye. The Aquila was a fairly ambitious project, and has been the subject of some excellent analysis.[x] It has become fashionable to blame "requirements creep" for the demise of the Aquila program. Further analysis suggests that this program had more problems than simply a problem with identifying a stable set of requirements. It suffices to say that a thoughtful review of the Aquila program would be beneficial to anyone contemplating an unmanned vehicle acquisition program for the U.S. Department of Defense. The Skyeye (a contemporary of Aquila) was a relatively large UAV used in Central America during the 1980's. It was superseded by the Sky Owl vehicle, which was created as a candidate for the now defunct U.S. Joint Services Short Range UAV program.[xi]

More recently, the Gulf War demonstrated that *automata* are not exclusively relegated as items of amusement, but rather can also serve as serious instruments of war. Examples of these military robots included cruise missiles, unmanned aerial reconnaissance drones, and remotely controlled tank hulls for minefield breaching.[xii] It is perhaps interesting to note that a review of the field of military robotics reveals that most work has concentrated on the

development of unmanned aerial or underwater vehicles, rather than unmanned ground vehicles, despite an apparently much broader range of applications for ground-based systems. However, there appears to be a fairly straightforward reason for this disparity of effort.

Since we human beings are creatures of the land, ground based applications tend to find it more difficult to show cost effectiveness (particularly during peace time.) Clearly, any vehicle which carries people into the air or under the sea must bear a significant cost penalty merely to sustain and protect its human crew. There are also some technical concerns which favor the aerial and undersea applications which will be discussed later. Nonetheless, the incredible lethality of modern precision weapons, the broad spectrum of operations facing the Army today, and the widespread intolerance for casualties among our people have combined to "raise the *ante*" regarding the potential need for unmanned ground vehicles. One need look no farther than Somalia to realize the truth of these concerns regarding the potential impact of a comparatively small number of U.S. casualties on national policy. Indeed, even when facing a fairly inept opponent as was the case in the Gulf War, losses from fratricide alone can potentially have dramatic political consequences.

TERMINOLOGY

The time and trouble already expended to try and define the term "robot" probably outweighs any benefit that is likely to be derived from the effort. Nonetheless, my personal favorite definition is that a robot is any device that can "surprisingly" (unexpectedly?) perform a task previously performed directly by humans; that is, today's robot may be tomorrow's smart appliance. A future automobile that can accept voice commands and maneuver itself using GPS may be considered a robot, at least for a time. The latest cruise missiles, too, are probably robots (note that cruise missiles and unmanned aerial vehicles are managed by the same joint program office). The key point is that future military equipment will almost certainly be more highly automated, maybe much more highly automated, and yet those systems will probably not be considered robots by the standards of their time, at least once they become familiar. Fortunately, there should be little if any capability degradation due to this inevitable nomenclature modification.

As already stated in the abstract, robotics may well represent the greatest unfulfilled technological promise of the late twentieth century. Part of the reason may be an unrealistic perception of *what* robots are. Karel Capek's play notwithstanding, real robots are fundamentally machines (tools), not androids (mechanical people). Acknowledging a tendency by many (including many in the research community) to succumb to an almost fanciful anthropomorphic bias, the simple reality is that there are no androids. For example, in the auto industry (the world's largest user of industrial robotics), robots are either articulated, reprogrammable, serial mechanisms that spray paint, spot weld, or "pick and place" parts, or they are automatically guided vehicles (AGVs) that move material around the plant by

following preset routes. Such robots are essentially "autonomous," in that they can operate without the need for continuous supervision by a human operator. This is due to the fact that there exists a large measure of structure inherent in both the task and the environment. The battlefield application is something else entirely.

Because most battlefield applications tend to provide little task structure and are performed in a dynamically unstructured environment, battlefield robots share little in common with most of the high-level control paradigms of their industrial counterparts. That is, it is usually impractical to simply preprogram a military robot to perform the same battlefield task repetitively. This is especially true if the robot is mobile, and for all practical purposes, the term *battlefield robot* has become virtually synonymous with *unmanned vehicle*, and more specifically unmanned aerial vehicle (UAV) and unmanned ground vehicle (UGV).

Unmanned aerial vehicles (also sometimes called remotely piloted vehicles (RPVs) for reasons to be discussed later[xiii]) are essentially conventional aircraft whereby no human is actually onboard during flight operations. A familiar example of a UAV is the radio-controlled (RC) model airplane flown by hobbyists. Battlefield UAVs, however, generally tend to be larger than most model airplanes due to the requirement to carry military payloads, tactical radio communications, and sufficient fuel for extended missions (though they are still usually smaller than comparable manned aircraft.)[xiv] It is worth noting that mini-RPVs quite similar in size to larger RC model airplanes, such as the Pioneer, continue in use today.

Unmanned ground vehicles are also essentially conventional ground vehicles which can be operated without a human being actually on board the vehicle during vehicle operations. Like UAVs, familiar examples include radio-controlled, model cars. However, today's UGVs, unlike UAVs, often make use of manned vehicle platforms which are then modified and

augmented to be remotely operated. This is generally driven more by economics than any esoteric design principle. Modern UAVs, on the one hand, can be made less expensive (usually much less) than corresponding manned aircraft simply by being able to neglect pilot ergonomics. UGVs, on the other hand, generally find that the economics of using a mass-produced ground vehicle platform outweigh any economic advantage of foregoing driver ergonomics. Furthermore, some UGVs are intentionally operated optionally as either manned or unmanned ground vehicles depending on the military situation and mission.

Unmanned underwater vehicles (UUVs) have become a significant commodity, both for civil as well as military (naval) applications. Nowhere is this clearer than in the off-shore oil industry, where UUVs have all but replaced commercial divers for repair and maintenance of off-shore oil rigs. Interestingly, UUVs were originally termed Remotely Operated Vehicles (ROVs) since, like the RPV, they were all "remotely operated" by a full-time human operator located aboard a controller ship or other maritime platform. However, as UUVs are not central to the Army's battlefield mission, they will not be addressed further, except for the occasional anecdotal reference to make a comparative point.

Arguably, the principal underlying technology of all unmanned vehicles is *control technology*.[xv] Indeed, the key technological issue regarding the design of any military unmanned vehicle system is the degree of autonomy this system will be required to exhibit. Robotic vehicles are generally considered to be those vehicles which are "autonomous, semiautonomous, or remotely controlled" [xvi] and exhibit a degree of "intelligent" behavior. The degree of autonomy is usually the critical issue in the design of an unmanned vehicle because it not only drives the cost of onboard navigation sensors and computational power, but also directly determines the nature of the required data links as well as the degree of operator skill

(and hence the sophistication of the man-machine interface) required. Consequently, it is also usually the key cost driver of any unmanned system design.

Levels of Control

Remote Control: The term "remote control" is used here to refer to the simplest (and generally least expensive) method by which we can realize an unmanned vehicle capability. Under this regime the operator directly commands those actuators necessary for the vehicle to operate, just as if he or she were actually on board the vehicle. That is, the remote operator directly steers, throttles, and brakes the ground vehicle. Early UAVs were operated in this fashion, hence the name "remotely piloted vehicles." The operator had to actually "pilot" the unmanned aircraft, just as if he or she were on board. This regime works fairly well at close range whereby the remote vehicle is under the direct observation of the operator. At greater distances, effective control can start to get problematic, primarily due to loss of orientation.

Teleoperated Control: As with remote control, teleoperated vehicles rely directly upon the operator's skills and reflexes to successfully control the unmanned vehicle. However, the operator can no longer directly observe the remote platform, but must be given some sense of remote presence (usually called telepresence) so as to function as though he or she were actually on board the vehicle. Telepresence usually consists of a video display, audio feedback, and often a map display. Some experimental designs include motion seats, back-drivable steering devices, and other kinesthetic devices. The penultimate choice would of course be a high-fidelity synthetic environment, or virtual reality environment, of sufficient accuracy so as to be indistinguishable from the experience of actually being on board the vehicle. Furthermore, this sense of telepresence must occur in real-time since the operator is in real-time control of the vehicle. An example might be the environment provided by a high

quality (and high cost) flight simulator. However, this approach creates a tremendous communication bandwidth requirement.

Semiautonomous Control: One method to reduce the communication bandwidth burden for control is to allocate some of the lower control functions to on- board computer control. The classic method for this is to navigate via waypoints. Here the operator specifies a sequence of target locations and the on-board computer must then generate the real-time command signals so that the vehicle reaches the commanded locations. This paradigm is extremely effective (and comparatively easy) in a relatively pristine, compliant, fluid environment as found for aerial and underwater vehicles. Ground vehicles have generally found this approach much more problematic. The reasons for this are twofold. First, the innermost control loops for ground vehicles tend to be much faster (with stability margins on the order of 100 ms) due to the fact that these vehicles must remain in contact with the "stiff" ground. Secondly, ground vehicles have a much more challenging task with regard to obstacles. These two factors combine to make out-of-sight, semiautonomous, unmanned ground vehicle control technically challenging.

Autonomous Control: Because of the more "technically benign" environment for unmanned aerial and underwater vehicles, autonomous systems already operate in these environs. Examples include advanced cruise missiles and anti-submarine torpedoes. Fortunately, the cognitive power required to support fully autonomous unmanned ground vehicles may be fairly close at hand. Some experts predict that gigaflop controllers may become "commodity items" ($5,000 or less) by the year 2000.[xvii] Given the ever-increasing demands by both the commercial and military sectors upon a fixed electromagnetic spectrum, combined with ever-diminishing costs for computing power, one is driven to conclude that the

trend will be toward ever more "autonomous" capability for all unmanned vehicles not unlike the similar trend toward "smart weapons."

Inextricable from a discussion of levels of control is the data link and man-machine interface requirements. Having specified one of the three (within the context of a given military mission and environment for its conduct), the minimum requirements of the other two are largely determined. That is, these three factors (level of control, data link capacity, and man-machine interface) basically determine a design space that has essentially only one degree of freedom.

Technologies

Data links are those communication links between the human operator and the unmanned vehicle which are needed to ensure mission accomplishment. These links are traditionally referred to as down-links and up-links. *Down-links* are those communications from the unmanned vehicle back to the operator. They consist primarily of status information and sensory data inputs required either to maneuver the vehicle, accomplish some mission task, or both. *Up-links* are those communications from the operator to the unmanned vehicle, which usually are of the nature of command signals. They serve to facilitate maneuvering the vehicle or to articulate some payload (such as pointing a sensor, grasping with a manipulator, or pointing and firing a weapon). These terms are fairly easy to remember if one recognizes that they have their roots in the early development of remotely piloted (aerial) vehicles.

Man-machine interface, sometimes termed *human factors engineering* in the Army, refers to the analysis and design issues relating to how one successfully executes the human contribution in the control paradigm. This discipline includes operator displays, input devices and mission management schema. Significant research in this arena has been accomplished in

recent years, particularly as relates to synthetic environments and simulation. While in concept the man-machine interface appears as mutually independent a variable as control level or data links, in practice the man-machine interface is generally a dependent variable driven by the choices of the other two.

Sensors are those devices that permit the mobile robot to both move in its environment, as well as to accomplish something useful during its mission without relying solely on preprogrammed or *a priori* information. These two functions thus represent a convenient way to organize our thinking about sensors for military robots, namely those sensors facilitating collision free navigation (navigation sensors) and those required for mission success (mission sensors).

Propulsion technologies represent another area of concern for military robots, though probably more for UAVs and UUVs than for UGVs. Propulsion technologies are those that facilitate the robot's mobility in its environment. They can range from conventional power plants, as is usually the case for UGVs since they often use conventional ground vehicle platforms, to the more exotic for special purpose vehicles. For UGVs, the topic also tends to include how the vehicle physically interfaces with the ground (wheels, tracks, or even legs).

ANALYSIS OF TECHNOLOGIES

Control Technology

Control technology, which in today's world is essentially synonymous with digital control, is an exciting field due to the breathtaking speed of the advances in microelectronics. The computational power of the standard microprocessor found in the typical desktop computer today far exceeds the power of the typical mainframe computer of only a few years ago. Revolutionary improvements in digital circuits promise to continue for at least another decade before physical and manufacturing limitations begin to slow the rate of progress.[xviii] This power is already manifesting itself in the latest generation of so-called smart weapons. The tomahawk cruise missile is a good example. By exploiting the computational power necessary to successfully execute terrain-matching algorithms, this weapon precludes the necessity of putting aircrews at risk attacking high value targets using traditional tactics.

Architectures

Serial Processors: Current estimates regarding the computational speed necessary to functionally approximate the human eye range from a hundred million to a billion operations per second, whereas guesses concerning the computational speeds needed to mimic the functions of the human brain range from ten trillion to ten thousand trillion operations per second.[xix] While present day computers are perhaps billions of times faster than humans at performing rote-mathematical functions, they are vastly inferior to the majority of the animal kingdom as regards tackling real world tasks. During the next few years, however, as supercomputers transition from gigaops benchmarks to teraops, military robotics can be expected to become much more sophisticated.

Parallel Processors: The advent of relatively cheap, "high speed microprocessor chips has facilitated the implementation of reliable, massively parallel computers in which parallel data streams and instructions streams allow a multitude of microprocessors to work on the same problem simultaneously."[xx] For example, as far back as 1991 the Defense Advanced Research Projects Agency (DARPA) developed a 64-unit parallel processor known as Aladdin, which could execute instructions at a maximum of one billion operations per second. This coffee-can-sized computer was developed to support military systems.[xxi] Using a similar architecture with a more modern chip such as the PowerPC 500-SPECmark, RISC-based, personal computer chip, one could expect to achieve about thirty-two billion operations per second. While limitations imposed by manufacturability may eventually curtail further advances, it is clear that computational power will continue to get better, faster, and cheaper.

Neural Networks: Neural networks are a computational architecture designed to emulate the functioning of an animal's nervous system. Such schemes are relatively well-suited to tasks involving pattern recognition, but must be trained using a number of examples. Furthermore, they must be retrained when the environment changes or new patterns are introduced. Neural networks have been used extensively by the DARPA UGV Demo II program. Here they served as the front end of machine vision systems for vehicle navigation and local obstacle avoidance. They are also used for automatic target recognition.[xxii] Genetic learning is a variation on the neural network as it shares the trait of optimization through learning. However, here we add the element of adding a factor of random selection from a "gene pool." This implies that the performance of a genetic learning system may not always be optimal, but the system should be able to adapt to the unexpected, given sufficient time and tolerance for trial and error.

Levels of Control

Remote Control: As previously described, remote control implies that the human operator performs the control functions for the unmanned vehicle as though he or she were actually on board. From a control perspective, this is the simplest (and generally cheapest) controller to implement. Its utility, however, is generally limited to those tasks whereby the unmanned vehicle is operated in very close proximity to the human operator. The only data link is usually a narrow-band, tactical channel below 80 Mhz which serves as the up-link. This type of control has actually been implemented for limited, short-distance, "brute-force" type applications such as minefield-breaching operations. During Operation Desert Storm a number of Kaman Sciences-built remote control kits were provided to the U.S. Marine Corps. These kits were originally developed to be used on old, M-60 main battle tanks which were intended for use as targets. The Marines planned to mount the kits on M-60 series hulls equipped with plow blades in order to breach the Iraqi defensive line. Unfortunately, the kits arrived in theater too late for use. Fortunately, the Marines were able to accomplish their breaching mission without significant casualties.

Teleoperated Control: As with remote control, the operator is responsible for the entire control function, but here he usually must operate the vehicle outside of his direct observation. This presents a vexing challenge if one is to be able to operate under a wide range of conditions. Firstly, assuming a competent down-link, the video imagery is likely to resemble "looking through a soda straw." Secondly, without a second, comparable link (for stereo), the operator has no depth perception. Experiments at the Robotic Vehicle Test Range at Sandia National Labs demonstrated that the result can often be a tipped over vehicle when operating in unfamiliar, challenging terrain.[xxiii] If one uses analog video signals, bandwidths on the order of

six MHz per channel are required (twelve MHz for non-field sequential stereo). Unfortunately, such bandwidths in the radio frequency (RF) spectrum to easily and robustly support real-time, analog video for several vehicles, especially if operating beyond direct (electronic) line-of-sight, are unavailable in many (if not most) locals. At the higher frequencies which are available, there exist propagation issues (particularly for unmanned ground vehicles) which will be discussed later. There has been some use of fiber-optic cable to provide a secure, wide-band, non-line-of-sight data link for UGVs. The principal disadvantages are cost, logistics, and robustness. There have been some successes, but the jury is still out regarding the widespread use of fiber-optic cable for battlefield UGVs.

As television systems convert from analog to digital, the bandwidths required can actually increase. For example, full-motion, full-color, 525-line digital video requires a bandwidth of 198.45 MHz, which is far greater than that required for a conventional, analog TV picture. However, by making use of intraframe redundancies and interframe predictabilities, current digital image compression techniques can effectively provide compression ratios on the order of 200:1 with negligible loss of perceived picture quality. This still suggests a required bandwidth on the order of one MHz, but reductions in picture quality (such as color range, resolution, and frame update rate) can permit the transmission of a small-picture, color video over voice-grade (25 kHz) transmission lines. Such imagery is inadequate to "teleoperate" a UGV (primarily due to signal latency), but further advances in digital video data compression (driven almost entirely by commercial applications) may soon permit the use of robust, tactical radio nets for the near real-time transmission of video imagery. UAVs and UGVs would no doubt be well-suited to exploit this opportunity.

Semi-autonomous Control: An effective technique for lowering the bandwidth requirements for unmanned vehicle control is that of giving the vehicle sufficient local autonomy to permit it to navigate from waypoint to waypoint without directly articulating the actuators, such as steering and throttle. This control scheme was first demonstrated successfully with UAVs. That is not surprising for two reasons. First, since UAVs operate in a fluid medium, their controller stability margins (the minimum required update rate for the controller to operate) are more generous. Secondly, obstacle avoidance is largely ignored, except for during the initial, pre-flight mission planning. UGVs on the other hand, must have a relatively fast controller update rate (on the order of ten times per second), since they operate in continuous contact with a "stiff" environment (the ground). Also, obstacle avoidance is a significant concern. Nonetheless, semi-autonomous control has been successfully demonstrated for UGVs, with the result being a dramatic reduction in the communication bandwidth requirements.

The Unmanned Ground Vehicle Joint Project Office (UGV JPO) demonstrated such a system, known as FELICS (Feedback Limited Control System).[xxiv] Here the driver's function is to indicate the desired vehicle path in a continuous fashion, with the task of following the path being allocated to the onboard computer. Using FELICS, a six-wheeled all-terrain vehicle has been successfully controlled using frame rates as low as one frame every three seconds. This scheme has been successfully demonstrated by the developer, AmDyn Corporation, using a voice-grade tactical radio channel. Interestingly enough, this approach also reduces the operators work load and fatigue as compared to teleoperation. Concerns regarding workload are not simply humanitarian. Quite the contrary, testing has shown that high operator workloads mean rapid degradation in system performance because the operator very quickly

becomes the "weak link" in the system. Reductions in operator workload tend to increase the overall performance of unmanned vehicles. Using the metaphor of the battle tank, under teleoperation the operator is the tank driver (albeit operating buttoned up due to the limitations of sensory feedback.) With FELICS, the operator is now the tank commander, still responsible for where the vehicle goes, but functioning at a reduced workload. Interestingly, the on board processor used for the first demonstrations of FELICS in 1992 was an INTEL 80386!

NASA's Jet Propulsion Laboratory continues to pursue research in computer-aided remote driving in conjunction with the lunar and Mars rover vehicles. For these applications, however, the frame update rates can be expected to be on the order of about one every several minutes. Consequently this effort may well have somewhat less applicability to a battlefield environment than some other efforts, such as FELICS. Perhaps even more technically interesting, within the U.S. Department of Defense, DARPA has sponsored significant research in support of autonomous vehicles.

Autonomous Control: Because of the dramatically lower control bandwidth requirements for aerial and underwater vehicles (due to their compliant, and relatively obstacle-free, fluid environments) "brilliant" autonomous aerial vehicles already exist in the form of the latest generation of cruise missiles. Because of the cognitive powers required to operate a fully autonomous UGV in a relatively unstructured (though domain specific) environment, full realization of this capability remains a few years off. (Returning to the main battle tank metaphor, here the human operator is either a platoon leader or even a company commander. He issues mission-type orders and employs the unmanned vehicles as his distributed, intelligent agents... the ultimate digital battlefield)!

During the 1980s DARPA and the U.S. Army Topographic Laboratories sponsored a trailblazing initiative known as the Autonomous Land Vehicle (ALV). By 1992, the DARPA-sponsored Autonomous Land Vehicle In a Neural Network (ALVIN) was able to autonomously drive down Interstate 79 for over 21 miles at a speed of 55 miles per hour. This testbed made use of a mechanical vision system developed at Carnegie Mellon University to monitor the location of the edge of the road.[xxv] In June, 1996, DARPA's UGV Demo II was more or less successfully completed. This initiative had the goal of developing (over a five year period) the technologies necessary to demonstrate the feasibility of a team of four supervised UGVs to execute a military mission in a simulated tactical environment. The three technological areas critical to successful mission accomplishment were those of mission planning and operator interface, mobility/perception, and RISTA (reconnaissance, intelligence, surveillance and target acquisition).[xxvi] Note that each of these areas stand to directly benefit from the increase in speed and availability of computing power.

Data Communications

Considerable attention over the years has been devoted to a fairly broad range of alternative data communications schemes (primarily for down-links). Geosynchronus-satellite communications are generally discarded from consideration for several reasons including propagation latency (as much as 500 milliseconds), susceptibility to jamming, and the relative scarcity (and cost) of available bandwidth. Low earth-orbit satellites are another possibility, due to their improved propagation characteristics, but the cost (due to the number required to keep at least one in view at all times) is probably prohibitive. Airborne relays, such as UAVs or balloons are an often-discussed alternative, though not without their own difficulties. Mission planning, antennae pointing, and time on station can be problematic, though the recent

establishment in the U.S. of an Aerostat acquisition program (even though oriented on cruise missile defense) may serve to mitigate some of these concerns as we climb the "learning curve." Micrometerite communications systems are considered too expensive and are functionally intermittent at best, while ultraviolet communications are very dependent on weather conditions, may be visible to the enemy, and can even be hazardous to personnel.[xxvii]

Thus, despite all this work, only two data communications alternatives have remained viable: fiber optics and Radio Frequency (RF).

Fiber Optics: The use of fiber optic cable in the domestic tele-communications industry in recent years has been little short of a revolution. The reason is simply that a fairly thin strand of "glass" cable can provide what, for nearly all practical purposes, is unlimited bandwidth. Further, this medium is jam proof, extremely secure from a data security perspective, and highly resistant to electromagnetic pulse (EMP). The military implications have begun to be recognized, as typified by the Army's Fiber Optic Guided Missile (FOG-M) program.

This weapon system, which is currently in at least its third incarnation as a developmental program, has the unique capability of allowing a single soldier to launch a relatively small, anti-tank/anti-helicopter missile from nearly any location, direct its flight to a designated area, and then terminally guide the missile to its target using a visual image transmitted in real-time back to the gunner via the fiber optic cable. Using such a system, the target has virtually no chance of using a last second counter-measure, such as using counter fire against the gunner (as is commonly the case with direct fire systems) or releasing chaff or flares to fool a radar or infra-red guided air defense missile. While fiber optic cable would be of questionable viability for a UAV application which required flights of long range and

extended duration (especially over enemy-controlled terrain), it has been used with some measure of success for the unmanned ground vehicle application.

Much of this work for the battlefield applications of UGVs has been performed by the Unmanned Ground Vehicles/Systems Joint Project Office in Huntsville, Alabama. The "classic" approach has been to use a reinforced, armored fiber (usually with a Kevlar coating) that was payed out by the UGV. After mission completion, the fiber was recovered for reuse.[xxvii] Unfortunately, the logistical burden associated with this strategy was generally deemed unacceptable for many conventional battlefield scenarios. More recently, however, single-use spools of FOG-M type fiber optic cable have been tried. This strategy has dramatically reduced the logistical burden associated with the use of fiber optic cable, (as well as the cost) and thus may well make it the medium of choice where electromagnetic security is mission essential, or when fiber optic cable's other unique attributes outweigh its limitations. Even so, there is little dispute that RF data communications is the essential mode for UAVs and the "preferred" one for UGVs.

Radio Frequency (RF): This mode of data communications (historically termed "wireless") generally refers to the use of that portion of the electromagnetic spectrum roughly from a few Mhz up to the tens (or even hundreds) of Ghz as the carrier frequency for the transmission of data. Obviously the ability to operate a remote vehicle without a physical tether is desirable for all military applications (if for no other reason than to eliminate an apparent vulnerability), and is an absolutely, non-negotiable requirement for many. As already mentioned, untethered flight is mission essential to virtually all UAV operational concepts and scenarios. While some UGV applications may permit the use of fiber optic cable

(particularly those that do not require the operator to be highly mobile) untethered operation is desirable here as well.

The process of choosing a suitable carrier frequency is generally based on three considerations:

1. Good propagation characteristics over the terrain associated with the mission environment (usually characterized by low data error rates even at low transmission power).
2. Ability to accommodate the required bandwidth.
3. Availability of the channel space for this application by using unit.[xxix]

The first parameter is driven by the terrain parameters of the mission environment. For UAVs, unless the mission calls for flying behind or through mountain ranges, the curvature of the earth tends to be the limiting propagation- related terrain issue. While UGVs tend to operate at much shorter ranges, these systems are much more vulnerable to signal blockage (due to natural or man-made obstacles), signal reflection (or multipath), and signal absorption (such as by foliage). The second parameter (as already discussed) is driven by the choice of control scheme (and related HFE issues). Based on physics, the carrier frequency must be greater than half the required bandwidth. However, regulatory requirements dictate that the frequency must be at least several times larger than the bandwidth in order to accommodate multiple channels per frequency band.[xxx] Obviously, the third parameter is a regulatory issue.

A lot of excellent work has been done in this arena including measurements (empirical data), modeling, and analysis. Some of the more noteworthy results include the following:

1. Ground communications losses can run as high as 70db higher than space-based communications losses.
2. Fast fading and shadow losses increase with frequency (as expected).

3. Frequencies below 100 Mhz require very aggressive data compression to support real-time video.
4. Frequencies above 10 Ghz require directional antennas of 10 db gain or higher (as well as tracking subsystems for antenna pointing).
5. Available frequencies between 100 Mhz and 1 Ghz are generally useable (if not ideal) for unmanned vehicle applications (including UGVs) without the need for either directional antennas or data compression (though antennas may need to be elevated to permit a minimum signal strength of 100 watts of transmission power).[xxxi]

Clearly, the key result is number 5. While robustness issues remain, the RF data communications problem is tractable, if we're serious about developing and fielding military robotic systems. This point is important as the RF communications issue has long been used as an argument to perennially postpone system development, at least for UGVs. Continued research, especially in computer-aided control and data compression will only improve the viability of unmanned vehicle systems, but they are clearly viable today!

Human Factors Engineering

Human factors engineering is important to the development of all military systems, but it has been an especially critical concern in the development of unmanned vehicles. The first UAVs were remotely piloted vehicles, with an operator's yoke often presented in front of the pilot, mounted to a chest plate he wore over his shoulders. Much of the recent history of UGVs can be traced to the Army's Human Engineering Lab (HEL), which was the forerunner of the Army Research Laboratories' Human Engineering Directorate (HED). The history and criticality of human factors engineering in the design and development of unmanned vehicles is closely linked to the degree of autonomy displayed by the unmanned vehicle.

Because modern military UAVs have become essentially semiautonomous vehicles (with auto launch, automatic landing/recovery, as well as "auto-pilot" in flight control) UAV operators need no longer be "pilots," and most are not. Most of the recent system development work for battlefield UGVs, on the other hand, has centered around teleoperation, with the Tactical Unmanned Vehicle (TUV) being the center-piece of those efforts. Recall that with a teleoperated system, the vehicle operator controls the vehicle as though he were on board. Success depends directly upon the operator's reflexes. The problem is exacerbated by the higher demands placed on operating a ground vehicle (as compared to vehicles in a fluid environment), especially tactical ground vehicles in the presence of obstacles, and especially when outside of direct observation by the operator. Essentially, the human factors problems which have surfaced in conjunction with the direct teleoperation of UGVs reside with the difficulties of providing a driver with an adequately realistic simulation of the cab conditions in the vehicle being driven (a real-time synthetic environment). Wide-angle displays are desirable not only for making turns and spotting things approaching from the flanks, but also in just keeping the driver oriented (remember the soda straw?). However, wide-angle displays require additional communications bandwidth as well as wide screen displays. Audio feedback has also been found to be beneficial, and is routinely provided on UGVs. Fortunately, audio feedback requires comparatively little bandwidth. Experimental testing has shown that a number of UGV "drivers" become nauseated when teleoperating a UGV for any length of time, perhaps due to the disparity between what the driver sees and what he senses in his inner ear, so-called kinesthetic dissonance. Fatigue is another problem, most likely due to the high degree of concentration needed to make up for the lack of "realistic" driving conditions.

(Interestingly, experiments at HED found this to be less of a problem among teenagers and young soldiers with a history of frequenting video arcades)!

Both head-mounted displays and various flat-screen displays have been evaluated for teleoperated UGV control. Full-color, high-resolution, head-mounted displays are difficult to implement and fatiguing to the operator. They also isolate the operator from his immediate surroundings; an arguably unacceptable situation for a battlefield system. Flat screen displays are often bulky, and are not easily adaptable to stereo display. However, recent advances in active matrix, color displays for notebook computers have improved matters. Also, novel stereo schemes such as using field sequential stereo (alternating the video display lines between a pair of cameras) have been demonstrated. Consequently, flat-screen displays have become the display of choice.

Another concern has been image stabilization. Lens stabilization systems are readily available for the driving camera(s). Alternately, the video image can be electronically stabilized. For UGV driving, an image stabilization scheme which filters out the high frequency and high-amplitude vibration has been shown to be optimal. Low-frequency and low-amplitude vibration should be retained as visual cues for the driver regarding road conditions. As noted, human factors engineering is most important during teleoperation.

While remote control also entails the direct control of actuators, it is typically executed with the remote vehicle under the direct observation of the operator, though video feedback may also be presented of the ground immediately in front of the vehicle. This direct observation of the robot provides context and global orientation to the control problem which is difficult to achieve during teleoperation. Thus human factors issues are generally less critical

during remote control. HFE issues are also less critical when the low level actuators are under computer control, as is the case with semi-autonomous and autonomous control regimes.

Other Technologies

Sensors: While there are a raft of second tier (other) technologies that are important to the development and fielding of military robots, sensors are no doubt first on this list. I have relegated sensors to this second tier, however, not because they are not critical, but rather because they tend to fall outside of the robotics research spectrum. This is primarily due to the wide availability of suitable sensor subsystems. That is to say, choosing a suitable suite of sensors for a military robot system tends to be an exercise in evaluating vendor brochures, rather than designing and then cobbling together breadboard/brassboard prototypes to test that design. As mentioned earlier, these sensors can be conveniently categorized as navigation sensors and mission sensors.

Navigation sensors are those sensors necessary in order to facilitate the unmanned vehicle's successful navigation from one place to another. This problem can be further decomposed into three sub-problems:

1. Moving the vehicle in a controlled and purposeful fashion,
2. Collision/obstacle avoidance,
3. And navigational referencing (knowing where you are).[xxxii]

The first category includes those sensors necessary to make the unmanned vehicle a controllable system. Included are items that range from speedometers at the higher control levels down to rotary encoders on the wheels to ensure a stable, closed-loop control regime, at the lowest control levels. This is normally the category of sensor where the designer begins,

since the ability of the system to be able to exhibit controlled, purposeful motion is a large portion of its *raison d'être*.

Having mastered controlled, purposeful motion, the next major concern is usually collision avoidance. Most of the focus here is usually placed on vision-based systems, especially when we are talking about a control regime where the human operator retains primary responsibility for collision avoidance (which is true for all but the most "autonomous control modes.") Although a bit dated now an excellent basic reference on the subject is *Robot Vision*, written by Berthold Klaus Paul Horn (published in 1986 by MIT Press.) A wide range of other sensors, such as acoustic and infrared sensors can be useful generally, but are essential for any significant degree of autonomous motion. A superb reference on this topic was recently published by a longtime friend and colleague, H.R. Everett, entitled *Sensors for Mobile Robots - Theory and Application*. I highly recommend it!

Having mastered controlled motion without running into things, the remaining problem is to know where you are. The standard technique is to rely on some form of dead reckoning.[xxviii] This usually is accomplished by using the combination of heading sensor (such as a magnetic compass to determine direction of travel) and odometry (such as wheel sensors counting rotations in order to determine distance traveled in that direction.) Accumulated navigational errors are periodically nulled out by using a "fix" on some known reference via some other navigational aid. Global Positioning System (GPS) receivers are an excellent example of these aids.

Mission sensors are those that facilitate the successful completion of some task, navigation of the platform not withstanding. Vision systems also play a large role here. In some applications, such as the FELICS system discussed earlier, the same sensor (video

camera) may alternate between serving as a navigation sensor and a mission sensor. Other mission sensors include range finders, forward looking infrared (FLIR) sensors, and motion detectors. Clearly, sensors are absolutely critical for unmanned vehicles. Fortunately, there is a rich domain of highly capable alternatives from which to choose.

Propulsion: Unmanned ground vehicle propulsion has been the subject of several studies, including a trade study by the U.S. Army Tank and Automotive Command.[xxxiv] This study found that six-wheeled vehicles seemed to offer great promise based upon the design parameters specified in the study. These findings were incorporated into the development of an early prototype known as the Surrogate Teleoperated Vehicle (STV). Some limited study continues regarding legged motion, though these efforts are primarily for NASA. Virtually all efforts in recent years having to do with military UGVs have down-played the relative importance of propulsion as a design issue in favor of the economics associated with utilizing the vast fleet of tracked and wheeled vehicles already available in military inventories.

For Unmanned Aerial Vehicles the propulsion issue is primarily one of the choice of a suitable power plant. Because they do not have to be man-rated, UAVs have been able to utilize rotary engines, which offer excellent power to weight ratios and are available in the power ranges needed by comparatively small UAVs. Unfortunately, these are gasoline-powered engines, and gasoline powered systems have otherwise been all but eliminated from the military inventory (both for logistical as well as safety reasons.) Hence there has been (and continues to be) extensive research to develop suitable "heavy-fuels" engines for the UAV application (using JP-5 or JP-8).

REPRESENTATIVE UNMANNED SYSTEMS

Unmanned Aerial Vehicles

A comprehensive description and analysis of just the current UAVs either fielded, under development, or contemplated would easily fill several volumes. This is true despite the fact that UAVs have been developed for only one mission area, namely as aerial reconnaissance platforms. (Note that the U.S. Army proponent for UAVs has been the Military Intelligence School at Fort Huachuca, AZ.) Consequently, I shall present only a few representative samples of systems from these categories. Hopefully these will illustrate the major issues and concerns.

Reconnaissance UAVs entered service in the U.S. in a fairly substantial way with the introduction of the Israeli-built Mastiff in 1983. This occurred on the heals of an abortive air strike in Lebanon in which two USN aircraft were shot down and a naval aviator was captured. Then Secretary of the Navy, John Lehman, was "incensed that the U.S. was risking tactical manned platforms to obtain target information in Lebanon while the Israelis were conducting the same missions with UAVs."[xxxv] The Mastiff, a remote-controlled UAV with a television camera, had very limited capability, but it was a start.

The Pioneer replaced the Mastiff in 1986, and remains in service with the Navy and Marines today (most recently flying missions in the Balkans). Capable of carrying infrared (IR) night or day television cameras, it is more capable than the Mastiff. However, it is not equipped with a Synthetic Aperture Radar (SAR), so its bad weather sensor capabilities are very limited. Originally it had no automatic take-off, landing or mission execution capability.

Such shortcomings are probably reflected in its high accident rates. Newer (more capable) systems are now available, though currently only in limited numbers.

The Hunter UAV, jointly produced by Israeli Aircraft Industries (IAI) and Thompson Ramo Wooldridge (TRW), was until recently the flagship program of the joint service's effort to acquire a family of UAVs. Hunter was to be able to operate from unimproved airfields, and be able to support Army division and Marine task force commanders. As the "baseline" system of the Joint Tactical UAV program, Hunter was the so-called "short range" variant, intended for use with both ground and maritime forces. (Under the joint service's initiative a "close range" UAV would be one which could operate within 30 km of its ground station, "short range" would nominally operate within 150 km (350 km with an airborne relay), and "mid range" would operate out to 650 km. This system of nomenclature and classification, however, appears to no longer be in use).

A modest number of Hunter systems are deployed with the Army. Five Hunter systems, each consisting of eight air vehicles and associated equipment, passed their acceptance tests in August, 1995. Currently, A Company of the Army's 15th Military Intelligence Battalion is equipped with (slightly less than two complete) Hunter systems. Although the Hunter acquisition program was formally terminated by the Army in 1996, the system seemed to give a good account of itself at the recent (March, 1997) Army Warfighting Experiments at the National Training Center in California.

The current "belle of the ball," at least in the tactical UAV arena, is the Outrider program. Termed the Joint Tactical UAV, the Outrider is intended to provide Army brigade, Marine Air Ground Task Force (MAGTF), and Navy commanders with a dedicated, tactical UAV system. Intended for both ground and maritime operations, the Outrider (built by Alliant

Techsystems) is to demonstrate automatic take-off, landing, and limited automated mission execution. (See figure 1.) These capabilities should successfully address some of the major sources of system failure in many previous UAV systems. Currently, this system is expected to be acquired as an Advanced Concepts and Technology Demonstration (ACTD), though recent technical problems have raised some doubts as to the political viability of this program, as well.

Several so-called endurance variants have been added to the fray, including the Medium Altitude Endurance (MAE), the Conventional High Altitude Endurance (CONV HAE), and the Low Observable High Altitude Endurance (LO HAE). These last three, however, are currently managed as Air Force efforts, directly under the auspices of the Defense Airborne Reconnaissance Office (DARO) rather than the UAV Joint Program Office. Note, however, that all UAV funding flows through DARO.

The Medium Altitude Endurance UAV, Predator, has recently been in service in Bosnia. With a range in excess of 500 miles and a mission endurance of 24 hours,[xxxvi] this system has proven very useful. Built by General Atomics, the sensor suite includes IR and day television imagery as well as SAR. The system is also highly automated. Like Outrider, Predator has also been acquired as an ACTD. The Air Force is the designated "force provider."

The conventional HAE is called Global Hawk. This system is projected to provide sustained, high altitude reconnaissance and surveillance. "With an endurance of 42 hours at altitudes in excess of 60,000 feet, it will loiter for 24 hours over a target area of up to 3,000 nautical miles from the launch area."[xxxvii] It is planned to be capable of carrying electro/optic (E/O), IR and SAR sensors simultaneously as well as being able to use wide-band, satellite-based and terrestrial line-of-sight communications.

Global Hawk will be complemented by Darkstar, for those missions where stealth is essential. The Darkstar concept calls for operational ranges of up to 500 miles with a loiter endurance of eight hours at 45,000 feet. Built by a Lockheed Martin/Boeing team, this system will employ the HAE Common Ground Segment (CGS) which provides for launch and recovery, mission control, and ground communications.

Unmanned Ground Vehicles

Unlike UAVs, unmanned ground vehicles have been conceived and often prototyped for a wide range of applications. Some of these applications have included RISTA platforms, weapons delivery platforms, countermine systems (including breaching, proofing, and clearing), explosive ordnance disposal, material handling, physical security, and others.

Perhaps the quintessential UGV development effort was the TMAP, developed by the U.S. Army Missile Command (MICOM). TMAP originally stood for Teleoperated Mobile Anti-armor Platform. Built during the waning days of the cold war in the late 1980's, TMAPs were intended to be small enough to be transportable in the back of a High Mobility Multipurpose Wheeled Vehicle (HMMWV). Mounted on board the TMAP vehicle was to be an imaging device (day television camera or IR) for local navigation and target acquisition, an acoustic sensor for queuing the operator to the presence of possible targets, and an anti-armor missile system. Remote control was realized primarily through connection to an operator control unit via a fiber optic data link (though an RF back-up link was also to be included). Secure, jamproof, and non-emitting, a fiber optic cable was ideal for a system intended to wait in the "Fulda Gap" for the onslaught of the Warsaw Pact tank armies. Two prototypes were built. One was done by Martin Marrietta and the other by Grumman Aerospace.

Much of the reason this program was unsuccessful was that halfway through the effort the mission changed (sound familiar?). Competing for dollars at a time when the Army had several developmental anti-tank missile systems, Congressional language dictated that the TMAP would focus on reconnaissance, and forego its anti-armor role. Reconnaissance generally demands a fairly high degree of mobility, a characteristic that was definitely not TMAP's strong suit (largely because it was never intended to be). Nonetheless, along with lessons learned from the Marine Corps' Teleoperated Vehicle (TOV), a similar developmental effort but based on the remote control of a modified HMMWV rather than a special purpose vehicle, the Unmanned Ground Vehicle Joint Project Office (UGV JPO) was born.

Based on this historical context, the Tactical Unmanned (ground) Vehicle (TUV) (as successor to the TMAP and TOV) has been the flagship acquisition program of the UGV JPO. Intended to be a first-generation UGV for RSTA, the concept envisions a "relatively small, light-weight, teleoperated, mobile ground system for U.S. Army infantry and USMC forces."[xxxviii] Such a system would permit a soldier or marine to operate the TUV from a safe location. The TUV thus permits the ground commander to extend his presence without putting his personnel at risk. Sensors may include day TV cameras for navigation and RSTA, IR, and acoustic sensors. "Other mission modules may include nuclear, biological, and chemical (NBC) surveillance and detection equipment, mine detection and neutralization equipment, and communications relays."[xxxix] It is the TUV that has been the context for which most of the discussion regarding control research and data link analysis takes place. However, because it is expected to support such a wide range of missions and mission profiles, it also presents the most technical challenges.

The UGV JPO also manages another program which, though much less technically challenging, (and perhaps because of it) has delivered immediate benefits. Known as the Vehicle Teleoperation Capability (VTC), the concept is to have a modular package which, when installed on a combat vehicle, turns a normally manned vehicle into a remote-controlled vehicle for selective, limited applications. The key enabler here is that the vehicle is remotely operated only from a fairly short distance (a few hundred yards at most), and under the direct observation (line-of-sight) of the operator. This dramatically simplifies both the data communication issue as well as the situation awareness problem. The main application so far has been for the countermine mission.

In October 1995 the Unmanned Ground Vehicles/Systems Joint Project Office,[xl] working in close cooperation with the U.S. Army Engineer School, was tasked to upgrade seven Panthers (turretless M-60 tanks with track-width, mine clearing rollers) with the Standard Teleoperation System (STSs) for deployment to Bosnia in support of Operation Joint Endeavor. (See figure 2). The STS is a state-of-the-art, digital teleoperation system that can be used to convert virtually any military ground vehicle into one that can be remotely operated for selected, hazardous missions.[xli] Built by Omnitech Robotics, STS also includes real-time video and audio feedback. This line-of-sight video system gives the remote operator a clear picture of the ground immediately in front of the Panther for precise, local navigation. (See figure 3). The system also permits the ability to rapidly change back and forth between manned and unmanned operation. The performance of these systems, which were used primarily for "proofing" an area that had already been "cleared," was excellent.

Indeed, the soldiers' response to the STS-equipped Panthers was outstanding. "On 29 June 1996, the 23rd Engineering Battalion, 'A' company, detonated an anti-tank mine during

proofing operations. While the tank sustained damage, the STS continued to operate."[xlii] More importantly, no U.S. soldiers were injured! On three other occasions so far, Panthers have detonated mines that otherwise would likely have killed or injured U.S. soldiers or civilians. In all these instances the Panthers, while proofing areas that had nominally been cleared of mines, detonated those mines and thus kept our soldiers out of harm's way. Land mines, and more importantly the U.S. casualties that they might inflict, are a relatively cheap and effective class of weapons that could represent an asymmetrical advantage for some potential adversaries, especially during so-called Operations Other Than War (OOTW). The VTC capability, as typified by the STS equipped Panther, goes a long way toward mitigating such an enemy's advantage across the full spectrum of conflict.

Another major concern facing the Army today is the increased possibility of Military Operations in Urban Terrain (MOUT). The Marines have clearly recognized the increased probability of such operations in the littorals. A system that holds a great deal of potential for such operations is one built by Westinghouse Electric Systems. Called Pointman, this UGV is intended for Military Operations in Built-up Areas (MOBA), especially during OOTW. (See figure 4.) This relatively small all-terrain vehicle can go through doorways and climb stairs. Operating in a tethered mode, it has a range of 500 feet. It also has an RF mode. Such a system permits soldiers and marines to safely enter buildings, deal with booby traps, and even employ non-lethal weapons (such as for crowd control) with little or no risk to the human operator. Thus, like VTC, Pointman can be particularly useful during operations like those recently in Somalia and Haiti. The proponent for this system within the Army is the U.S. Army Engineer School at Ft. Leonard Wood, MO. They are also the proponent for the VTC.

FUTURE VISION

As the previous section would suggest, much has been written about the future role of robotics in military affairs. In fact the word robot is virtually ubiquitous in any discussion of future military issues. Furthermore, there seems to be a general consensus that this role will be significant. The Navy, already the lead service for the Unmanned Air Vehicle Joint Program, appears to be on the verge of extending its interests more aggressively in the unmanned underwater arena, particularly to enhance our submarine warfare capabilities. While the Navy has already successfully fielded remotely-controlled, UUV mine-hunting systems, this new initiative seems to go far beyond that.

Called Manta, this new, sleek, UUV would be embedded in a submarine's body for deployment when needed, "especially for dangerous operations in shallow water."[xliii] It is believed that such a system could dramatically reduce the risk to manned submarines, which are increasingly required to operate in shallow water near an enemy's coastline. Working with the Defense Advanced Research Projects Agency (DARPA) to build a prototype within five to six years, Manta could be operating with the fleet by 2010, though that is probably a bit optimistic.

The change of heart by the U.S. Air Force regarding UAVs in the last few years is nothing less than extraordinary. After Vietnam, the Air Force completely withdrew from the UAV arena, no doubt viewing such systems as a direct threat to their (manned) aviation acquisition programs. Today the Air Force seems to be posturing to take over the UAV arena altogether. "UAVs will play a commanding role in the 'new' USAF of the 21st century, service officials said at a recent air power conference in London."[xliv] Potential applications

being considered range from surveillance and reconnaissance to aerial combat. The USAF has even gone so far as to establish the U.S. Air Force Unmanned Aerial Vehicle (UAV) Battlelab.[xlv] This does not mean that UAVs will not continue to meet with resistance in the USAF community, but rather that there has been a pragmatic recognition at the highest levels of the Air Force of the inevitable growing importance of UAVs to the aviation mission area. However, to some it may appear to be the old "if you can't beat them, join them" (and then take over) paradigm.

Not to be totally outdone, the Army is also beginning to accelerate its acceptance of unmanned vehicles, at least for UAVs, anyway. While the Army's manifested desire for an unmanned reconnaissance drone dates back at least to the Aquila program,[xlvi] recent war games at the U.S. Army War College clearly demonstrated other Army needs for UAVs, such as to be able to serve as "surrogate satellites" when necessary.[xlvii] The USAF Global Hawk is arguably such a system.[xlviii] Able to operate from 12 miles up, this UAV is expected to help "U.S. forces achieve information dominance" according to Paul Kaminski, the Under Secretary of Defense for Acquisition and Technology.[xlix] Additionally, the Hunter UAV was one of the real success stories at the recent Force XXI Warfighting Experiments, as already noted. Perhaps more significantly (for our soldiers), this increased Army interest is not totally limited to UAVs.

Unmanned Ground Vehicles (UGVs) are also expected to play a dramatic role in the Army's future. One role being actively discussed is in the area known as "terrain dominance." Smart, mobile mines are expected to provide a new dimension to the ground commander's ability to dominate maneuver. Equipped with sensors and a top attack munition, the wide area mine known as Hornet is already being produced by Textron Defense Systems. A much larger and more capable version (which includes mobility) known as Raptor (named for the

velociraptor in the movie "Jurassic Park) would be so versatile that "it could be thought of as a combined arms unit, capable of performing military intelligence, combat engineering, or armored cavalry missions."[l] By today's standards, Raptor is definitely an armed UGV. (Contrary to popular legend, there is no ban against such systems. If there were, land mines would already be outlawed). It should be noted that the STAR 21 study in 1993 predicted that such "robots" would play a dramatically important in the early part of the 21st century.

Besides the systems already discussed earlier, there are a number of emerging UGV applications and spin-off systems in the works. One is for fire-fighting. Wright Labs at Tyndall AFB is the DoD lead for this effort under Project Reliance. The plan is to use robotics to "navigate the firefighting vehicle to the site of the fire and then assist the human firefighters in delivering suppressant."[li] Another aviation oriented initiative is the so-called "next generation munitions handler." The idea is to exploit robotic capabilities to handle and load aircraft munitions. Obviously both of these efforts are applicable to Army aviation as well. Another particularly interesting project is one known as BUGS.

The proliferation in the use of improved conventional munitions (ICM) has spawned a tremendous challenge in our ability to clear large areas of unexploded ordnance (UXO) left by an attack using these systems. With ever greater use of ICM in conventional artillery applications, the problem will only grow.[lii] Fortunately, the system concept known as Basic UXO Gathering System (BUGS) may hold the answer. BUGS consists of "an autonomous or semiautonomous sensor platform to localize the ICMs and several small, expendable, autonomous vehicles that use the location data to proceed to the area and perform the required mission."[liii] Such a system might also be used for other, similar tasks, such as placing anti-mine

munitions. Besides these system concepts, there also exists a number of ideas for component technology spin-offs.

As the technology development efforts within the Joint Robotics Program (JRP) continue to bear fruit, the opportunity for spin-offs to manned systems proliferate. One obvious example is the robotic technologies planned for incorporation into the Crusader artillery system, including the associated Future Armored Resupply Vehicle (FARV).

Among the robotic features already decided on or being considered are an autoloader, automated technical fire control and gun laying for individual tubes, automated docking of the FARV, and automated transfer of munitions from the FARV to the Crusader gun platform. These robotic features reduce response time, increase fire rate, allow a single weapon to deliver multiple rounds that arrive simultaneously, permit greater flexibility in target allocation among weapons in the same battery, reduce crew exposure to enemy fire during resupply, and reduce manpower requirements.[liv]

As one might expect, there has been a fairly extensive technology effort conducted under the auspices of the JRP.

Known as the UGV Technology Enhancement and Exploitation (UGVTEE) program, this effort seeks to rationalize and harmonize robotics technology development efforts, both inside and outside the JRP's arena. Areas of technical interest have included automated mission planning, automatic target acquisition and tracking (including stationary targets in clutter), and simultaneous cooperation of distributed systems. Foremost in these efforts has been the development of a robust, autonomous navigation capability. Much has been achieved, though there remains much yet to do. Fortunately, time is on our side to a great degree, as these efforts continue to benefit from better, faster, and cheaper computational power. Indeed, the future benefits to our military potential may stagger the imagination and go well beyond the prognostications of even the most rabid robotics supporters. Consider the

following. A recent study published by the U.S. Army War College, as part of the Army After Next Project, predicts that:

> The fusion of the information, mechanical, and biological revolutions will eventually change the way military power is applied as well. Close engagements involving human soldiers may become an historic anachronism superseded by combat between robots or cyborgs. Such a situation will, of course, only come to pass after the careers and even the lives of today's political and military decision makers. But, it is equally true that directions set by contemporary decisionmakers, especially those concerning the human dimensions of technology, its social functions, and ethical constraints, will shape the future.[lv]

Obviously, if we choose the context of the discussion far enough in the future, issues become easy because of their perceived (immediate) irrelevance. The fact is that the choices we begin to make now are highly relevant to how, for better or worse, this capability will evolve and mature. Central to this issue is the role we shall allocate to battlefield robots for the near term, Army XXI (2000-2010).

RECOMMENDATIONS

THE INNOVATOR MAKES ENEMIES OF ALL THOSE WHO PROSPERED UNDER THE OLD ORDER, AND ONLY LUKEWARM SUPPORT IS FORTHCOMING FROM THOSE WHO WOULD PROSPER UNDER THE NEW.

Niccolo Machiavelli

It is fairly clear from reading documents like *Joint Vision 2010* and *Army Vision 2010* that information technologies will likely dominate the Army's investment strategy for the coming decade. Consequently, any realistic recommendation regarding an investment strategy concerning battlefield robots must recognize this reality. Such systems must obviously contribute to our warfighting potential in a dramatic way (so-called silver bullets), and must also be compatible with what may truly be a revolution in military affairs in the Army After Next. I believe that the following recommendations comply with these constraints, and thus offer a viable, worthwhile, affordable, and executable acquisition strategy to ensure that we are on an appropriate "glide path" to the future.

Unmanned Aerial Vehicles

I believe that the Army's history with UAVs has generally been a most unfortunate one. This history has been characterized by almost universal misunderstanding, widespread (though certainly well intentioned) mismanagement (at least from a business perspective), and bureaucratic meddling that is almost beyond comprehension. It would be humorous were it not for two facts. The first is that an astounding amount of resources has been squandered at a time when resources are increasingly scarce. Second, and certainly worse, is that our soldiers must continue to operate without the capability these systems would have provided.

My recommendation is a simple one. Make an unwavering commitment to the brigade level (tactical UAV) effort. To wit, charter a program manager, provide the resources

commensurate with the requirements, vest him with adequate authority, hold him responsible, and shield him (as much as possible) from the vagaries of higher headquarters. That won't be easy, nor will it guarantee success, but without taking those steps we will guarantee yet another failure. Also, don't shoot the program the first time there is a technical hiccup. (Remember that the first five F-4 Phantoms crashed during test flights, but the Navy and Air Force went on to buy thousands of them)! Don't start a new program when the next contractor comes in with a new proposal. (Paper systems always work better than the real thing)!

There will surely be challenges, but the benefits of fielding this system will be incalculable. Not only will this capability be available, but the genius of the American soldier will then have an opportunity to gestate. What we will learn about tactical UAVs within the Army's operational environment will undoubtedly posture us to successfully transition to an even better capability for the Army After Next. Let the USAF field "endurance" systems. Let the Navy field "maritime" systems. Together let's field joint systems where requirements are compatible. Regardless, the Army needs a tactical (brigade level) UAV now. Successfully fielding the tactical UAV capability will pay dividends to the Army far beyond the cost of investment. We must not fail yet again.

Unmanned Ground Vehicles

UGVs require a similar, determined strategy, though there are a few special twists. Unlike UAVs, the "ground" has generally not been as well-prepared for the introduction of UGVs. The exception to this statement may be found in the Corps of Engineers. The school at Fort Leonard has aggressively pursued robotics as a "tool" to accomplish its mission. Perhaps more than any place else in the Army, they have been able to overcome any instinctive

technophobia associated with "robots," and have embraced the capability these systems can provide (especially for "brute force" missions like countermine and obstacle reduction).[lvi] Therefore, I recommend that the Army aggressively pursue the fielding of at least two UGV systems. These are the Standard Teleoperation System (STS) and the Pointman system. The reasons are compelling.

The STS will ensure that our combat engineers will be able to rapidly breach mine fields so as to be able to maintain the momentum of any attack in mid to high intensity operations. In less intense environments, STS-equipped vehicles like Panther will be able to safely clear (and more importantly proof) various routes as was demonstrated in Bosnia. The financial investment is small, but the benefits in casualties prevented are huge. As land mines have become one of those "asymmetry" weapons favored by many of our potential adversaries, the VTC capability is needed now. Fortunately, as has been demonstrated in Bosnia, the STS system is mature and available now. Consequently, the UGV JPO should empowered (directed and resourced) to field the system without delay.

The other battlefield asymmetry that robotics can help with now is in the area of military operations in urban terrain (MOUT). Pointman-type systems are essentially modified, civil police robots currently in service around the world. They can deal with mines and boobytraps without risking soldiers, thus denying our adversaries what they often seek most, U.S. casualties on the six o'clock news. These robots can go into places where the risk is high. Note that the recent Joint Strategy Review concluded that in the future, "most combat will take place in urban areas where enemies can easily mix with the civilian population."[lvii] Robots can employ non-lethal devices without fear, since they cannot be injured or killed. In short, while they will never eliminate the need for highly trained and ready infantrymen, these UGVs can

give the Army another asymmetrical advantage in executing its responsibility as a full-spectrum force.

There are other systems that hold promise, but as the history of the UAV appears to demonstrate, we seem incapable of successfully fielding a range of revolutionary capabilities at the same time, if for no other reason than a lack of resources. Acquiring any system is difficult and expensive. That is doubly so for revolutionary systems. Given the maturity of the STS and the general availability of police-type robots (Pointman), however, the chances for success are high, the risks are low, and the costs affordable. What is lacking is the will (and the minimal resources of course) to execute the program.

Besides the immediate warfighting capabilities these systems will provide, the exposure of large numbers of soldiers to the utility of UGVs will help lay the ground work for more fully exploiting this capability in the years to come. As one young American soldier (who had just returned from Bosnia) proclaimed, "I'm sold on robotics. It worked for me in Bosnia!"[lviii] Without such exposure, however, it's doubtful such developmental efforts will occur, or at least in as timely a fashion. One should also note that the U.S. and its allies do not have a monopoly on this technology. It would certainly be unfortunate if in the next century, the American soldier's first experience where UGVs are used decisively on the battlefield occurs when those robots are used, not by him, but against him!

EPILOGUE

Sometime in the not too distant future, events will almost certainly occur whereby the need for these unmanned systems will be fully realized by the American people. Recall that these are the same people who have entrusted us with their sons and daughters. What's more, these systems (especially the recommended UGVs) are very affordable by the standards of modern weapon systems. Should those events occur, I pray we will not have to admit that we could have protected those sons and daughters, that we could have given them the tools to do their job without having to be put in harm's way, but chose not to.

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[ii] Steven M. Shaker and Alan R. Wise, *War Without Men - Robots on the Future Battlefield* , Pergamon-Brassey's, Washington, DC, 1988., p. 14.
[iii] Karel Capek, *Rossem's Universal Robots*, P. Selver (translation, New York: Washington Press 1973), Originally published in 1921.
[iv] Shaker, p. 15.
[v] Warwick E. Stanton, "The Development of Unmanned Ground Vehicles Up to 1945 - Lessons Learnt and the Relevance for Today," *Proceedings of the Association for Unmanned Vehicle Systems, International (AUVSI)* , Orlando, Florida, 1996, p. 459.
[vi] E.F. Ziemke and Bauer M.E. (1988) *Moscow to Stalingrad: Decision in the East*, New York: Military Heritage Press, 1988, p. 309.
[vii] Shaker, p. 22.
[viii] Shaker, p. 22.
[ix] Shaker, p. 27.
[x] William D. Knox, *of Gladiators and Spectators AQUILA A Case for Army Acquisition Reform*, USAWC Military Studies Program Paper, University of Texas, Austin, Texas, June, 1994.
[xi] Jim Bledsoe and Jim Schneider, "Sky Owl: A Total System for the 90s," *Unmanned Systems: The Magazine of the Association for Unmanned Vehicle Systems*, Vol. 9 No. 1, p. 38.
[xii] Colonel Jeffrey Kotora, USMC, interview by author, 7 January 1997, Notes, Redstone Arsenal, Alabama, Project Manager of the Unmanned Ground Vehicles/Systems Joint Project Office,
[xiii] Shaker, p. xi.
[xiv] Mark L. Swinson, "Military Robotics," *Encyclopedia of Computer Science and Technology*, Allen Kent and James G. Williams, eds., Marcel Decker, Inc., New York, 1993, pp. 309-328.
[xv] It is worth noting that the Army's unmanned aerial vehicle and unmanned ground vehicle programs are not located with the Army's (manned) air vehicle or ground vehicle agencies. Rather, both unmanned vehicle programs are collocated with the US Army Missile Command. The rationale is simply that while a number of technologies must be successfully integrated, the essential prerequisite for a viable unmanned system is a robust, remote control implementation, and the resident expertise in this technology resides principally in the guided missile community.
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[xx] Swinson, p. 314.
[xxi] LTC Erik Mettala, U.S. Army (Retired), interview with the author and briefing charts, 4 June, 1996. LTC (Ret) Mettala was the DARPA program manager for DEMO II.
[xxii] ibid.
[xxiii] J. Bryan Pletta and Michael D. Harris, "SARGE - Surveillance and Reconnaissance Ground Equipment," *Proceedings of the annual symposium of the Association for Unmanned Vehicle Systems* , Washington, DC, July, 1995, pp. 511-516.
[xxiv] *Unmanned Ground Vehicle Master Plan*, published under the direction of the Office of the Director for Tactical Warfare Programs, U.S. Office of the Secretary of Defense, as an annual report to Congress, Washington, DC, July, 1994, p. 18.
[xxv] A safety driver was always present.
[xxvi] *Unmanned Ground Vehicle Master Plan*, published under the direction of the Office of the Director for Tactical Warfare Programs, U.S. Office of the Secretary of Defense, as an annual report to Congress, Washington, DC, October, 1996. pp. 30-35.

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[xxxvi] Krulak, p. 12.
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[xlii] Lt. Col. Jon Moneyhun and David W. Parish, "Team Panther Keeps Soldiers Out of Harm's Way," *Unmanned Systems: The Magazine of the Association for Unmanned Vehicle Systems,* Vol. 14 No. 3, pp. 21.
[xliii] Robert Holzer, "U.S. Navy Manta may Extend Sub Combat Power," *Defense News*, Vol. 12 No. 11, pp. 1-11.
[xliv] Nick Cook, "USA's Revolutionary Plan for Air Vehicles Unveiled," *Jane's Defense Weekly*, Vol. 27 No. 10, pp. 5.
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[xlvi] William D. Knox, p. 1.
[xlvii] Sean D. Naylor, "U.S. Army War Game Reveals Satellite Vulnerability," *Defense News*, Vol. 12 No. 10, pp. 50.
[xlviii] William Matthews, "USAF Plans Global Hawk Tests, - Pilotless Spy Aircraft to Start, Fly, Land Autonomously," *Defense News*, Vol. 12 No. 10, pp. 24.
[xlix] ibid, p. 24
[l] George I. Seffers, "Robots Aid Army Terrain Control," *Defense News,* Vol. 12 No. 10, pp. 1.
[li] *1996 Unmanned Ground Vehicle Master Plan*, p. 28.
[lii] The author participated in a joint working group on this issue in 1993 at Redstone Arsenal, AL. The problem really first became apparent after Desert Storm. There appears to be a doctrinal problem as well. ICM are not mines, so our combat engineers consider the problem outside their mission area. However, the large numbers of unexploded bomblets produced by even a relatively modest attack completely overwhelms the capability of our Explosive Ordnance Disposal (EOD) teams. Doctrinally, their job is to "render safe" UXO. The number, dispersion, and field expedient tactics associated with handling these bomblets probably more closely resembles our approach to clearing mines. What's more, field artillery representatives at this meeting advised us that virtually all conventional and missile artillery was converting over to ICM in the near future. At last check, the issue of who would be responsible for clearing these UXO remained contentious and unresolved.
[liii] *1996 Unmanned Ground Vehicle Master Plan*, p. 28.
[liv] ibid, p. 29.
[lv] Steven Metz, *STRATEGIC HORIZONS: The Military Implications of Alternative Futures*, Strategic Studies Institute of the U.S. Army War College, Carlisle Barracks, PA, March 7, 1997, p.6.

[lvi] In fairness it should be observed that these combat engineer missions are among the most technically feasible at this point for the successful employment of UGVs.

[lvii] Robert Holzer, "QDR's high tech focus bothers officials," *Army Times*, April 7, 1997, pp. 26.

[lviii] Statement made by Sergeant Dennis Mitchell, B Company, 16th Engineer Battalion, regarding the use of the STS-equipped Panther vehicle for minefield-proofing operations in Bosnia, during the Pathfinder Association for Unmanned Vehicle Systems, International Symposium, Huntsville, Alabama, April 16, 1997.

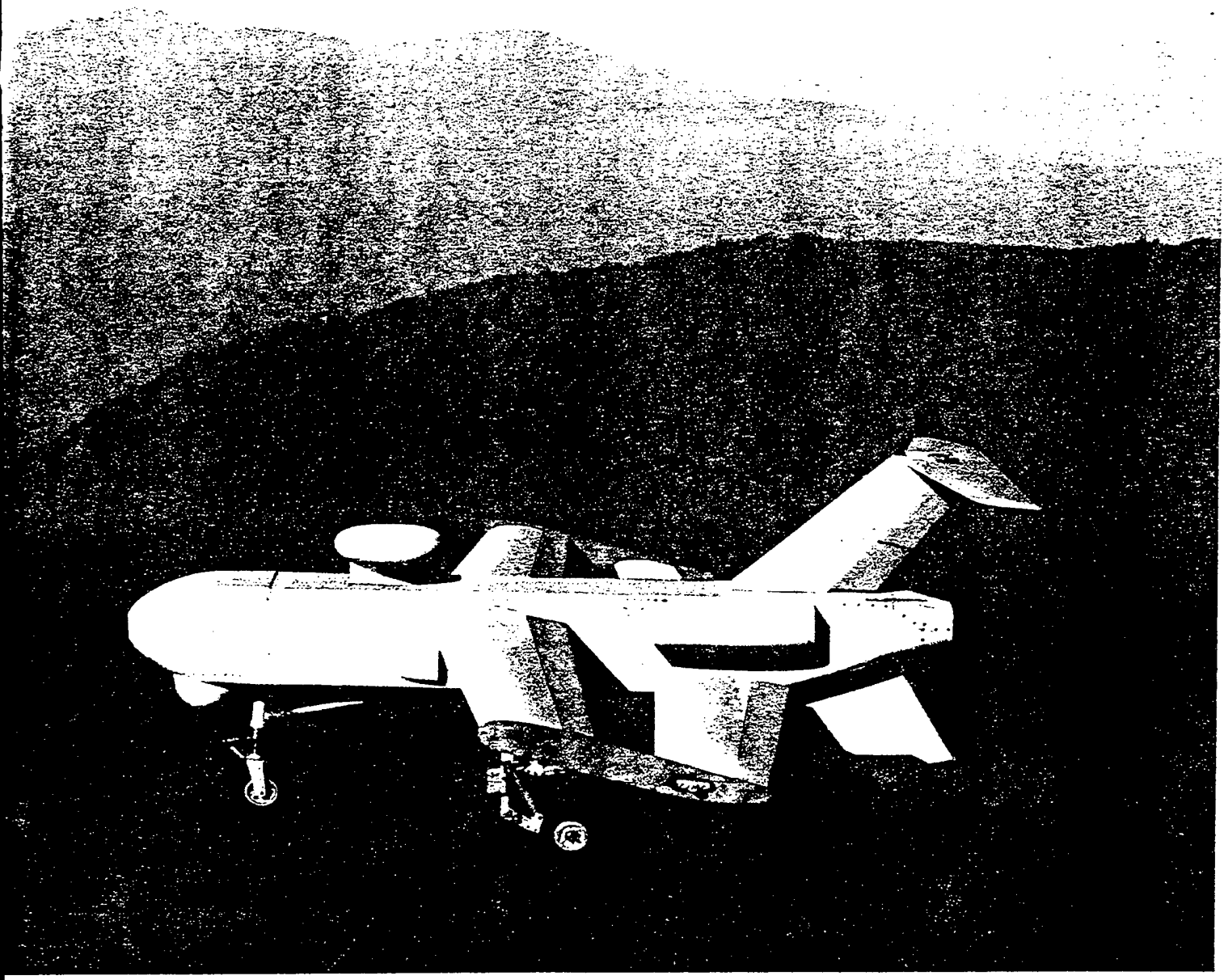


Figure 1. The Outrider Joint Tactical Unmanned Aerial Vehicle, Built by Alliant Techsystems.



Figure 2. The STS-equipped Panther vehicle (a turret-less M-60 main battle tank equipped with track-width mine rollers) on duty with the U.S. Army in Bosnia.



Figure 3. U.S. Soldiers training on the operator control unit for the Standardized Teleoperation System (STS), built by Omnitech Robotics.

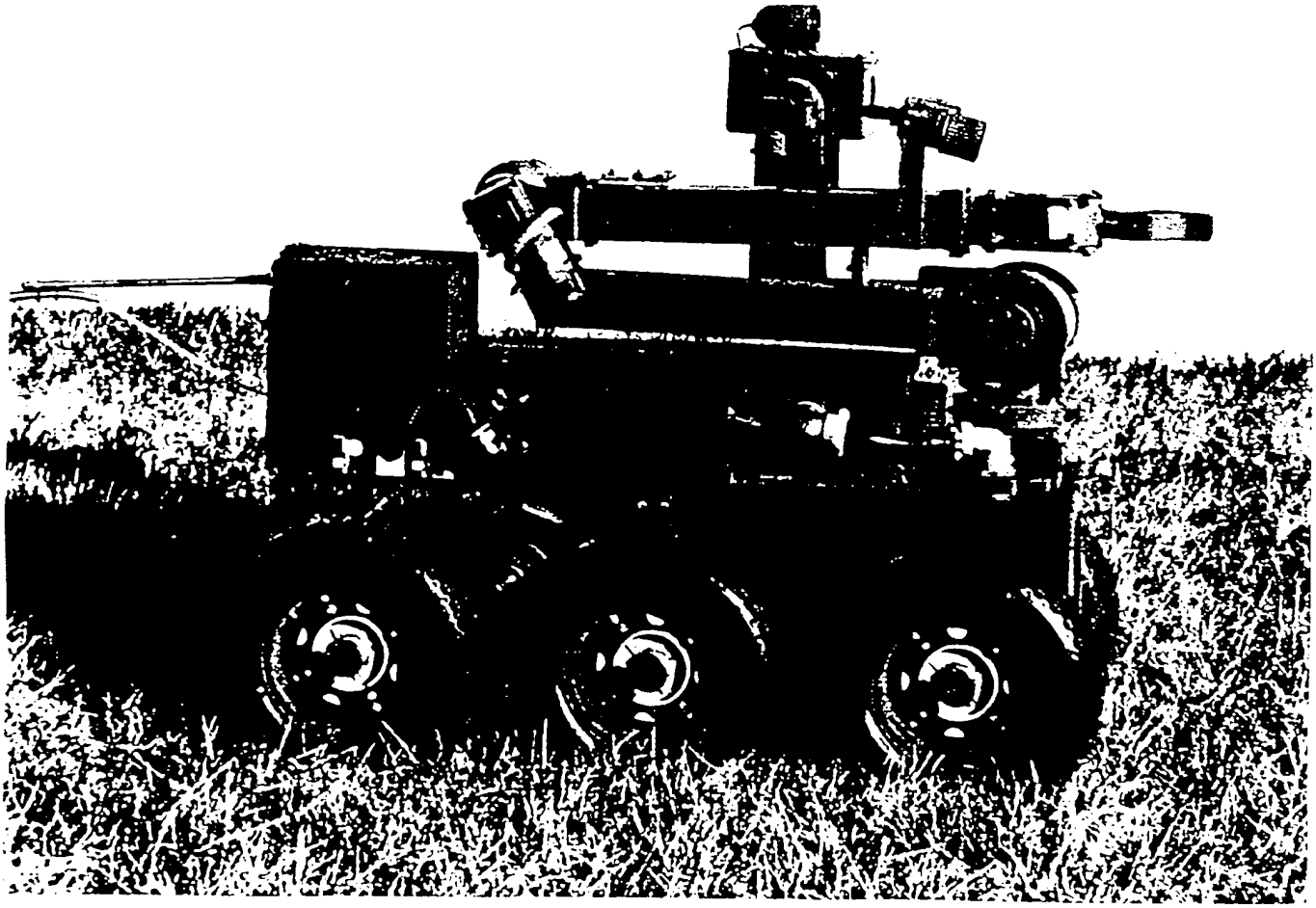


Figure 4. The Pointman unmanned ground vehicle built by Westinghouse Electronic Systems.